CHARACTERIZATION OF SOFT SOIL USING MULTI-CHANNEL ANALYSIS OF SURFACE WAVES (MASW) AND ELECTRICAL RESISTIVITY METHOD (ERM)

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For my beloved mother and father

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ABSTRACT

This thesis demonstrates the research on the soft soil characteristics using geophysical methods. The need on non-intrusive, time efficient, economic and larger volume of investigation had increased the demand of using geophysical methods for geotechnical investigation. The research concentrates on the determination of soft soil shear-wave velocity (Vs) profile using the multi-channel analysis of surface waves (MASW) and the soil stratigraphy using Electrical Resistivity Method (ERM). The soft soil Vs and stratigraphy were determined and correlated with the peat sampler and borehole data to obtain more accurate data. The research was conducted at Parit Nipah and RECESS UTHM. The Vs obtained for peat and soft clay at Parit Nipah was in the range of 29.7 to 34.9 m/s and 36.8 to 76.9 m/s respectively. While, the soft clay Vs obtained at RECESS was in the range of 64.4 to 124.0 m/s. The lower Vs obtained on peat compared to soft clay was due to the heterogeneity of peat. The soil strata obtained by ERM had good agreement with the peat sampler and borehole data. The resistivity value of peat and soft clay obtained at Parit Nipah was in the range of 47.2 to 127.7 ohm.m and 9.4 to 25.8 ohm.m correspondingly. While, at RECESS soft clay, the resistivity value was in the range of 1.0 to 4.6 ohm.m. The lower resistivity value of soft clay was governed by the amount of clay fraction which was related to cation exchange capacity (CEC). As higher CEC results in higher conductivity. The relationship obtained between the 1-D Vs and 1-D resistivity value shows that consistent value of peat Vs was followed by the slight decrease in peat resistivity value. While, drastic increase in soft clay Vs results in a significant decrease in soft clay resistivity value. This concluded that stiffness does not produce significant effect on the soil resistivity. Overall, MASW and ERM produced high quality data for subsurface investigation in larger volume with timely efficient manner and more economic.

ABSTRAK

Tesis ini menunjukkan kajian mengenai ciri-ciri tanah lembut menggunakan kaedah geofizik. Keperluan terhadap kajian tidak intrusif, cekap masa, ekonomi dan isipadu kajian yang lebih besar telah meningkatkan permintaan terhadap kaedah geofizik untuk kajian geoteknik. Kajian ini difokuskan dalam mendapatkan ciri-ciri berkenaan halaju gelombang ricih tanah lembut menggunakan kaedah *Multichannel Analysis of Surface Waves (MASW)* dan mengenal pasti jenis strata tanah menggunakan *Electrical Resistivity Method (ERM)*. Halaju gelombang ricih tanah lembut dan strata tanah diwujudkan dan dibandingkan dengan maklumat tanah yang diperoleh dari penyampel tanah gambut dan lubang gerudi untuk memperoleh data yang lebih tepat. Kajian ini telah dijalankan di Parit Nipah, dan RECESS UTHM. Halaju gelombang ricih yang diperolehi untuk tanah gambut dan tanah liat lembut di Parit Nipah adalah masing-masing dalam lingkungan 29.7 ke 34.9 m/s dan 36.8 ke 76.9 m/s. Manakala, bagi tanah liat lembut yang diperoleh di RECESS adalah dalam lingkungan 64.4 ke 124.0 m/s. Halaju gelombang ricih yang rendah diperoleh di tanah gambut berbanding tanah liat lembut adalah kerana sifat kepelbagaian yang terdapat pada tanah gambut. Lapisan strata tanah yang diperoleh menggunakan kaedah *ERM* dipersetujui oleh data pensampel tanah gambut dan data lubang gerudi. Nilai kerintangan tanah gambut dan tanah liat lembut yang diperoleh di Parit Nipah adalah sejajar dalam lingkungan 47.2 ke 127.7 ohm.m dan 9.4 ke 25.8 ohm.m. Manakala, pada tanah liat lembut RECESS, nilai kerintangan adalah dalam lingkungan 1.0 ke 4.6 ohm.m. Nilai kerintangan pada tanah liat lembut yang rendah dipengaruhi oleh bilangan pecahan tanah liat yang berkait rapat dengan kapasiti pertukaran kation. Kadar kapasiti pertukaran kation yang tinggi menyumbang kepada kekonduksian yang tinggi. Hubungkait di antara halaju gelombang ricih tanah satu dimensi dan nilai kerintangan satu dimensi menunjukkan bahawa nilai konsisten halaju gelombang ricih tanah gambut diikuti dengan sedikit penurunan pada nilai kerintangan tanah gambut. Manakala, penurunan drastik pada halaju gelombang ricih tanah menghasilkan sedikit penurunan pada nilai kerintangan tanah liat lembut. Dapat disimpulkan bahawa kekakuan tidak menghasilkan kesan ketara terhadap kerintangan tanah. Secara keseluruhan, *MASW* dan *ERM* menghasilkan data berkualiti untuk kajian sub strata tanah untuk isipadu yang lebih besar dengan kaedah lebih berkesan dan lebih ekonomi.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

c	Damping coefficient
c_c	Critical damping coefficient
CEC	Cation exchange capacity
D	Damping ratio
D_{min}	Minimum damping ratio
dx	Receiver spacing
ERM	Electrical Resistivity Method
f-v	Frequency-velocity
G_{max}	Maximum shear modulus
h	Thickness
I	Current
Lo	Array line offset distance
MASW	Multichannel Analysis of Surface waves
ρ	Density
R	Resistance
RMS	Root mean square
RMSE	Root mean square error
S/N	Signal to noise
V	Voltage
V_p	P-wave velocity
V_s	Shear-wave velocity
X_1	Source offset
Z_{max}	Maximum depth of investigation

LIST OF APPENDIX

CHAPTER 1

INTRODUCTION

1.1 Research background

Nowadays, geophysical method had been widely used in geotechnical investigation. Some of the methods which are commonly used are Multichannel Analysis of Surface Waves (MASW) and Electrical Resistivity Method (ERM). The application of the geophysical method in soil investigation, especially concerning soft soil is very limited. Hence, this research focused on the application of geophysical method on the soft soil investigation.

Geophysics method, such as MASW is designed to map spatial variations in the physical properties of soil. The main advantage of MASW is its ability to take into full account the complicated nature of seismic waves that always contain noise such as unwanted higher modes of surface waves, body waves, scattered waves, traffic waves, etc., as well as fundamental-mode surface waves (Park et al., 2007). The MASW method is divided into two, which are, active and passive. The active MASW method was introduced in geophysics in 1999. It adopts the conventional mode of survey using an active seismic source (e.g., a sledge hammer). It utilizes surface waves propagating horizontally along the surface of the measurement directly from the impact point to receivers. MASW also gives shear-wave velocity (Vs) information in either 1-D (depth) or 2-D (depth and surface location) format at a cost effective and time-efficient manner. The maximum depth of investigation (z_{max}) is usually less than 30 m, but this can vary with the site and type of active source used (Park et al., 2007).

The ERM is a geophysical method used to determine the subsurface resistivity distribution by injecting current into the ground through two current electrodes (C1 and C2), and measuring the resulting voltage difference at two potential electrodes (P1 and P2) (Loke, 1999). The Electrical Resistivity Method comprises of a 1-D sounding survey, 2-D imaging survey and 3-D surveys. The ability of 2-D Earth resistivity measurement to map the electrical resistivity distribution in the Earth allows the estimation of the subsurface heterogeneity (Slob, 2004).

Soft soil is considered as challenging soil especially due to its special features and high degree of compressibility. Peat is a representative material of soft soils and classified as highly organic with organic content more than 75% (Kolay et al., 2011). It is brownish in color and is formed by decomposed organic matter that have accumulated over a thousand years, with lack of oxygen and under waterlogged conditions. Peat is well known to deform and fail under light surcharge load, and it is characterized with low shear strength (5-20 kPa), high compressibility, high organic content (>75%) and high water content (>200%) (Zainorabidin and Wijeyesekera, 2007). While, clay is a fine-grained soil material that become plastic due to their water content and non-plastic when dried. The clay soil material also combines one or more clay minerals with traces of metal oxides and organic matter.

1.2 Problem statement

Geotechnical investigation is a critical pre-construction work especially concerning the soft soil. Various parameters are determined and observed during the investigation which include surface exploration and subsurface exploration. Dynamic soil properties and soil stratigraphy are some important parameters in subsurface exploration. Dynamic soil properties determination especially the shear-wave velocity is considered an important parameter when dealing with super structure and large construction. As mentioned by Ivanov et al. (2015), stiffness properties of near surface materials are important for engineering applications and shear-wave velocity is directly related to stiffness. It is also a critical parameters in geotechnical earthquake engineering problems. While, the soil stratigraphy provides description of the soil physical characteristics.

The dynamic soil properties and soil stratigraphy are conventionally collected by boring. This method is intrusive, takes longer time and higher cost before the data are obtained. The advancement of geophysical method in the past few decades allowed the investigation of subsurface exploration to be done in more time efficient manner and non-intrusive way. MASW method and ERM are some example of geophysical method used in subsurface exploration. The MASW method provides the shear-wave velocity profile of soil. The shear-wave velocity is one of the important parameters in determining the shear modulus which is one of the key factors to determine the soil stiffness. While, the ERM generates the soil stratigraphy and provides the resistivity value of the soil. In this research, the efficiencies of both methods were investigated to provide better alternatives in geotechnical investigation in future works.

Several doubts also arises regarding the optimization of the MASW method and ERM to provide reliable and high accuracy data. Hence, investigation of the data acquisition configuration and data analyzing are included in this research. The main purpose is to compare different configuration and data analyzing to achieve the best results. Therefore, the application of MASW method and ERM with the optimum configuration, will allow the subsurface exploration of the geotechnical investigation being done in a more time efficient manner and non-intrusive. Thus, providing knowledge to develop safer and more economic engineering design with efficient construction technique.

1.3 Aim

The purpose of this research is to establish soft soil profile using MASW method and ERM.

1.4 Objectives

This research embarks the following objectives:

i. To determine shear-wave velocity (Vs) profile of soft soil using Multichannel Analysis of Surface Waves.

ii. To identify the effect of different receiver spacing on MASW dispersion curve resolution.
iii. To determine the soft soil stratigraphy and resistivity value using Electrical Resistivity Method with complementary from peat sampler and borehole data.
iv. To establish correlation between 1-D shear-wave velocity profile and 1-D resistivity value.

1.5 Scope of research

This research focused on the establishment of soil profile at Parit Nipah and RECESS. The active 1-D MASW method and 2-D ERM were used to obtain the shear wave velocity and resistivity value (soil stratigraphy) respectively. Schlumberger and Wenner protocol were used for the ERM. The depth of peat layer at Parit Nipah was determined using peat sampler. While, the depth of soft clay at RECESS was determined from the borehole data obtained from the previous study.

1.6 Significance of research

The research focused to establish soft soil profile by applying the MASW and ERM. The data obtained from the analysis can be utilized for many useful applications. First of all, the shear-wave velocity and shear modulus are critical engineering parameters which concerned the stiffness of a soil layer. Therefore, good understanding regarding these dynamic properties allowed the engineers to tackle problems encountered during construction on soft soil. Next, the resistivity value allowed the determination of water table and mapping of soil stratigraphy. The data will give further understanding regarding soft soil, which will give benefit on how to deal with soft soil. These findings also will help engineer to design sustainable construction on soft soil site. Other than that, the results obtained may be used as preliminary studies for other soft soil experiments in the future.

1.7 Thesis layout

This thesis comprises the following contents:

i. Chapter 1: This chapter explains the core of this research such as the purpose, objectives and scope.
ii. Chapter 2: This chapter describes the soft soil characteristics and dynamic behavior. Geophysical method namely MASW method and ERM also described with all the necessary terms involved in this research. Previous researches regarding the topic also included.
iii. Chapter 3: This chapter explains the method used in this research in details. The method includes 1-D MASW method, 2-D and 1-D ERM and peat sampler.
iv. Chapter 4: This chapter shows the results obtained from this research. The results were also discussed and compared with the previous researcher.
v. Chapter 5: This chapter provides the conclusions and recommendation for further study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explained theoretically all the definitions, terms and keywords, related to this research. It includes the definition of geophysics, seismic, Multichannel Analysis of Surface Waves (MASW), the applications of seismic, Electrical Resistivity Method (ERM), resistivity, the applications of resistivity and soft soil. The previous results with similar interest from previous researchers were also listed.

2.2 Soft soil

The soft soil is considered as the most challenging soils compare to other type of soil. According to Vermeer and Neher (1999), high degree of compressibility is the special features of this type of soil. Near-normally consolidated clays, clayey silts and peat are categorized as soft soil (Vermeer and Neher, 1999).

2.2.1 Peat soil

Peat is an accumulation of partially decayed vegetation or organic matter that is unique to natural areas called peatlands or mires. In Malaysia, the natural vegetation of peatlands are mostly peat swamp forest and others comprise of natural vegetation of sedges, grasses and shrubs (International Wetlands, 2010).The peatland ecosystem is the most efficient carbon sink as peatland plants capture the CO_2 which is naturally released. Peat soil usually dark brown or black in colour, often with distinctive smell (Whitlow, 2001). Peat is classified as highly organic with organic content more than 75 percent and represent the extreme form of soft soil (ASTM, 2002). Peat properties reflect the peat environment, development process of peat and the types of peat-performing plant (Kolay et al., 2011).

The total area of peat soils in Malaysia is 2,457,730 ha which is 7.45% of Malaysia's 32,975,800 ha total land area (International Wetlands, 2010). The area division of the Malaysian peat soil is as shown in Table 2.1. Sarawak owned 69.08% of total peat soil in Malaysia which is the largest area followed by peninsular Malaysia 26.16% then Sabah 4.76%. Most of the lowland peatlands in Malaysia have developed along the coast and some had developed far inland along the former coastline (International Wetlands, 2010).

Table 2.1: Peat soil distribution in Malaysia (International Wetlands, 2010)

Region	**ha**	**%**
Sarawak	1,697,847	69.08
Peninsular Malaysia	642,918	26.16
Sabah	116,965	4.76
Total	**2,457,730**	

The peat underlying mineral soil are usually clay and sand (International Wetlands, 2010). The International Wetlands (2010) state that the water table of peat must be 20-30 cm below the peat surface or higher to prevent peat decomposition and drying out which will subsequently release carbon dioxide (CO_2).

The physical properties of peat consist of decomposition degree, water content, specific density, bulk density, etc. The decomposition degree of peat has a large range of variation. Peat can be classified into low, moderate and high decomposition according to the degree of decomposition (Jinming and Xuehui, 2002). The absorption capacity and water retention capacity of peat can be measured. *Spagnum* peat has the highest humidity and water content, whereas the herbaceous-woody peat has the least. According to Jinming and Xuehui (2002), the specific density of peat, which has a close relationship with the components of the plant residues found in peat, is relatively low, usually ranging from 1.0 to 1.6 Kg m$^{-3.}$ The bulk density of peat, depending upon the ash content, decomposition degree and components of plant residues, is also low, usually ranging from 0.1 to 0.5 Mg m^{-3} (Jinming and Xuehui, 2002). Table 2.2 shows the characteristic of organic material according to their degree of decomposition, while, the degree of humification according to the Von Post scale was shown in Table 2.3.

Table 2.2: Characteristic of organic material according to their degree of decomposition (Soil Survey Stuff, 1999)

	Fibric	Hemic	Sapric
Wet bulk density	<0.1	0.07-0.18	>0.2
Fibre content	2/3 vol. before rubbing 3/4 % vol. after rubbing	1/3-2/3 % vol. before rubbing	<1/3 vol. before rubbing
Saturated water content as percent of oven-dry material	850 - >3000	450 - >850	<450
Colour	Light yellowish brown or reddish brown	Dark greyish brown to dark reddish brown	Very dark grey to black

Table 2.3: The Von Post scale of humification (Von Post, 1922)

Symbol	Description
H1	Almost all the plant residues are still present; water in the peat is transparent.
H2	The plant residues are barely decomposed; water is transparent but with a light brown colour.
H3	Small amount of plant residues are decomposed; water is turbid and brown.
H4	Small amounts of plant residues are decomposed; water is very turbid, but the peat cannot flow between the fingers.
H5	The plant residues are somewhat decomposed, but the organisms can still be discerned; water is brown and very turbid; small parts of the peat can flow between the fingers.
H6	Large quantities of the plant residues are decomposed; about 1/3 of the peat can flow between the fingers, and the remains of plants left in the hand can still be discerned.
H7	The plant residues are highly decomposed and about ½ peat can flow between the fingers; the water is clear in colour.
H8	The plant residues are highly decomposed and 2/3 of the peat can flow through the fingers; plant remains in the hand are hydrolysed rootstocks and the woody material.
H9	Fully decomposed; all parts are fluid and the organisms cannot be discerned.
H10	Fully decomposed; the peat is all washed away with water.

2.2.2 Clay soil

Clay soil is a fine-grained soil material that combines one or more clay minerals with traces of metal oxides and organic matter. According to Unified Soil Classification System (USCS), the grain size of clay is <0.075 mm (Stevens, 1982). Generally, clays are defined as particles smaller than 0.002mm (Das and Sobhan, 2014). The clay minerals are complex aluminum silicates composed of two basic units: (1) silica tetrahedron and (2) alumina octahedron (Das and Sobhan, 2014). Clays become plastic due to their water content and non-plastic when dried.

The clay particles carry a net negative charge on their surface and in dry condition the negative charge is balanced by exchangeable cations (Das and Sobhan, 2014). Therefore, the presence of clay minerals provide cation exchange sites and has a great influence on the soil conductivity (Huat et al., 2014). According to Long et al. (2012), high clay content contribute to very low resistivity values.

2.3 Dynamic behavior of soil

In geotechnical earthquake engineering problems, the determination of dynamic soil properties is extremely important and critical task. The applications include geotechnical design applications, site characterization, settlement analyses, seismic hazard analyses, site response analysis and soil-structure interaction (Heureux and Long, 2016). Dynamic soil properties includes shear wave velocity (V_s), shear modulus (G), damping ratio (D) and Poisson's ration (v) (Luna and Jadi, 2000). According to Kishida et al., (2009) research on dynamic properties of highly organic soil are limited which only consist of Union Bay in Washington State (Seed and Idriss, 1970), Queensboro Bridge in New York (Stokoe et al., 1994), Sherman Island in California (Boulanger et al., 1998; Wehling et al., 2003), Mercer Slough in Washington State (Kramer, 2000), and Ojiya City in Japan (Tokimatsu and Sekiguchi, 2007).

Luna and Jadi (2000) also stated that dynamic soil properties are strain-dependent and to have compatibility between the results of different methods when the strain level overlaps is challenging. Therefore, the strain level must be ensured similar for comparison of dynamic soil properties using different methods. The estimation of shear modulus and shear wave velocity at low strain level are contributed by the evaluation of dynamic soil properties (Kumar et al.,2014). Table 2.4 shows some testing that allows the measurement of dynamic behavior of soil with different strain level.

Table 2.4: Field and laboratory test employed for dynamic investigation of soil (Kumar et al., 2014)

Field tests		Laboratory tests	
Low strain (<0.001%)	High strain (>0.01%)	Low strain (<0.001%)	High strain (>0.01%)
Seismic reflection Seismic refraction Steady-state vibration Spectral and Multi-channel analysis of surface waves (SASW and MASW) Seismic borehole survey (cross-hole, down-hole and up-hole) Seismic cone test	Standard penetration test (SPT) Cone penetration test (CPT) Dilatometer test (DMT) Pressuremeter test (PMT)	Resonant column test Ultrasonic pulse test Piezoelectric bender element test	Cyclic triaxial test Cyclic direct shear test Cyclic torsional shear test

2.3.1 Shear wave velocity (V_s)

Shear wave velocity is equal to the square root of the ratio of shear modulus (G), which is a constant of the medium, to density (ρ) of the medium as mentioned in Equation 2.1.

$$v = \sqrt{G/\rho}. \qquad (2.1)$$

According to Bessason and Erlingsson (2011), shear-wave velocity is a key parameter to compute the stiffness of a soil layer. The increases in shear-wave velocity causes increases in material shear strength (rigidity) (Ivanov et al., 2008). Therefore, the shear-wave velocity is directly proportional to the stiffness or rigidity. This critical parameter also is important in an earthquake hazards investigations and can be used to determine the respond of the highway and the highway structures in the event of an earthquake (Anderson et al., 2007). Table 2.5 shows site class definition according to International code council, Inc., (2000).

The shear-wave velocity model can be generated in 1-D, 2-D and 3-D. In this study using the MASW method, the 1-D shear-wave velocity model is considered. According to Luo et al. (2009), under the assumption of a mildly lateral shear-wave velocity variation, the inverted 1-D shear-wave velocity model is obtained from the average of the Earth covered by the geophone spread.

Table 2.5: Site class definition (International Code Council, Building Officials, 2000)

Site Class	Soil Profile Name	Average Properties in Top 100 feet (as per 2000 IBC section 1615.1.5) Soil Shear Wave Velocity, V_s	
		Feet/second	Meters/second
A	Hard rock	$V_s > 5000$	$V_s > 1524$
B	Rock	$2500 < V_s \leq 5000$	$762 < V_s \leq 1524$
C	Very dense soil and soft rock	$1200 < V_s \leq 2500$	$366 < V_s \leq 762$
D	Stiff soil profile	$600 < V_s \leq 1200$	$183 < V_s \leq 366$
E	Soft soil profile	$V_s < 600$	$V_s < 183$

2.3.2 Past research on shear-wave velocity (V_s)

The determination of shear-wave velocities of soil has grown intensely due to its importance in dynamic soil properties. Many researches have develop soil shear-wave velocities using different method at different type of soil. Table 2.6 shows some of the previous research using different type of method at soft soil location.

Table 2.6: Summary of previous research regarding soil shear wave velocities

Type of soil	Initial water contents (%)	Shear wave velocities (m/s)	Method	Remarks
Clay	20-80	50-300	MASW, SCPTU, CHT, SASW	(Heureux and Long, 2016)
Peat (Parit Sulong, Johore)	-	40-55	MASW	(Zainorabidin and Mad Said, 2015)
Peat (Pontian, Johore)	-	21-67	MASW	(Zainorabidin and Mad Said, 2015)
Soft clay	-	88-95 45-95	SASW, Hand vane shear test	(Zainudin et al., 2015)
Peat	-	80-110	MASW	(Rafiu and Ganiyu, 2014)
Peat	-	<100	SASW	(Bessason and Erlingsson, 2011)
Organic soils	-	81-87	- Seismic downhole OYO Suspension P-S logging system	(Kishida et al., 2009)

Table 2.6: Summary of previous research regarding soil shear wave velocities (continued)

Organic soils	-	83-90	Seismic downhole OYO Suspension P-S logging system	(Kishida et al., 2009)
Stiff clay	-	170-190	Lightweight deflectometer (LWD)	(Ryden and Mooney, 2009)
Boulder clay	-	200-700	MASW	(Hodgson et al., 2009)
Clay	-	80-140	MASW	(Long et al., 2008)
Clay and sand	-	180-230	MASW	(Anderson et al., 2007)
Soft clay	60-65	80-140	MASW	(Long and Donohue, 2007)
Peat	151-205	100-120	Seismic downhole	(Moreno et al., 2004)
Peat (fibrous)	236-588	22-27	Seismic downhole OYO Suspension P-S logging system	(Wehling et al., 2003)
Peat (fibrous)	152-240	88-129	Seismic downhole OYO Suspension P-S logging system	(Wehling et al., 2003)
Peat	236-588	21-30	Seismic downhole OYO Suspension P-S logging system	(Wehling et al., 2001)
Peat	171-185	80-165	Seismic downhole OYO Suspension P-S logging system	(Wehling et al., 2001)
Marine clay	-	117-207	Downhole test and CSW	(Leong et al., 2000)
Peat	500-1200 (average 600)	12-30	Seismic cone testing	(Kramer, 2000)
Peat (very fibrous)	-	81-87	Bender element tests	(Boulanger et al., 1998)
Peat (very fibrous)	-	83-90	Seismic downhole OYO Suspension P-S logging system	(Boulanger et al., 1998)

Some researchers had investigated the accuracy of MASW method in obtaining shear-wave velocity by comparing the results with several method such as borehole data and down-hole seismic survey. Oh et al. (2003) mentioned that, the percentage of difference between the V_s obtained by MASW method and down-hole seismic is only 9%. The shallow 5m depth showed the highest difference which result from insufficient high frequency components in the dispersion curve (Oh et al., 2003). The study done by Xia et al. (2002) regarding the comparison between the V_s obtained using borehole and MASW method showed that the difference between both measurements are random and approximately 15% or less.

2.4 Soil resistivity

Soil resistivity is defined as the measurement of how much soil resist to the flow of electricity. Subsurface electric resistivity distribution measurement in 2-D allows the estimation of heterogeneity (Slob, 2004). The soil resistivity value also is considered as one of the critical factor to determine the grounding system. Different type of soils have different resistivity and conductivity value. Materials resistivity varied greatly from one another, thus, measuring the resistivity of unknown material has the potential to identify the material (Herman, 2001). The resistivity of soil depends on the degree of saturation, the resistivity of pore fluid, porosity, and shape, size of particles (Kim et al., 2011). The surface conductivity of the colloids (i.e. clay or/and humus) and presence of ions also shows significant effects on the soil resistivity (Huat et al., 2014). The resistivity value is very dependent on water content (Reynolds, 1997). Table 2.7 displayed the resistivity of some of the common geological materials.

Table 2.7: Resistivity of common geological materials (Everett, 2013)

Geomaterial	Resistivity (Ωm)
Clay	1-20
Sand, wet to moist	20-200
Shale	1-500
Porous limestone	$100\text{-}10^3$
Dense limestone	$10^3\text{-}10^6$
Metamorphic rocks	$50\text{-}10^6$
Igneous rocks	$10^2\text{-}10^6$

The resistivity value in peat is governed by the unique characteristic of peat According to Ponziani et al. (2011), CEC, organic content, structure, heterogeneity pH and water content strongly affected the peat conductivity. The conductivity of peat pore water usually increases with depth and the peat bulk electrical conductivity is high (El-galladi et al., 2007). The electrical resistivity of peat decreased as the water content or temperature increased and the resistivity increased as the organic content increased (Asadi and Huat, 2009). Higher degree of peat decomposition resulted in a lower resistivity value (Asadi and Huat, 2009). According to Asadi and Huat (2009), highly decomposed peat have a higher CEC, higher negative charge and have higher quality and quantity of chargeable colloidal particles which resulted in a lower electrical resistivity. The CEC are the main factor in determination of peat electrical conductivity in normal condition, whereas at the more acidic site, organic matter and water content are more influential (Walter et al., 2016).

The presence of clay or the clay layer often shows very low resistivity value. The presence of clay fraction provide cation exchange sites, thus, contributes to lower resistivity (Huat et al., 2014). Jakalia et al. (2015) measured the resistivity of saturated clay and concluded that the presence of saturated clay contributed to very low resistivity zone. The resistivity of clay is ranged from 1 – 100 ohm.m with 30 – 40 % water content and 100 – 200 ohm.m for dry clay.

Application of resistivity method shows arising confidence with several correlation either with borehole data or among the geophysical methods. Delineation of alluvium zone (10 – 800 ohm.m) and granite bedrock (>2500 ohm.m) using 2-D resistivity which is agreed by the borehole data (Ali et al., 2013). Table 2.8 shows the summary of some soil resistivity value obtained by the previous researchers.

Table 2.8: Summary of previous study on soil resistivity value

Type of soil	Resistivity (Ωm)	Method	Remarks
Clay	1 – 50	2-D resistivity imaging	(Nordiana et al., 2013)
Silty clay	28 – 3036	Resistivity	(Abidin et al., 2012)
Clayey silt	54 - 3036	Resistivity	(Abidin et al., 2012)
Silty clay	<100	Resistivity (dipole-dipole array)	(Kim et al., 2011)
Highly decomposed peat	10 – 30	Resistivity cell	(Asadi and Huat, 2009)
Very slightly decomposed peat	10 – 50	Resistivity cell	(Asadi and Huat, 2009)
Clay	0.8 – 20.8	Time domain electromagnetic	(El-galladi et al., 2007)
Peat	0.2 – 0.9	Time domain electromagnetic	(El-galladi et al., 2007)

2.5 Geophysics

Geophysics is a field that combine the understanding of geology, physics and mathematics in order to understand the Earth. However, the term often restricted to denote the physics applied to the ‘solid earth’ which by means, exclude the hydrosphere and atmosphere (Sharma, 1997). The study of Earth processes includes the laboratory experiments, computational and theoretical modelling, remote imaging, and direct observation.

Geophysical exploration is one of the main field study in solid earth geophysics. It has rapidly expended over the years with the introduction of several methods and techniques. In geological and geotechnical investigation for civil engineering problems, a large area must be investigated. Therefore, geophysical method provide useful tools in such wide area investigations. The summary of 12 commonly used geophysical surveying methods for geotechnical investigations were listed in Table 2.9.

Table 2.9: Summary of 12 commonly used geophysical surveying methods for geotechnical investigations (Anderson et al., 2008)

Geophysical Method	**Measured Parameter(s)**	**Physical Property or Properties**	**Physical Property Model (Geotechnical Application)**	**Typical Site Model (Geotechnical Application)**
Shallow seismic refraction	Travel times of refracted seismic energy (p- or s-wave)	Acoustic velocity (function of elastic moduli and density)	Acoustic velocity-depth model often with interpreting layer boundaries	Geologic profile
Shallow seismic reflection	Travel times and amplitudes of reflected seismic energy (p- or s-wave)	Density and acoustic velocity (acoustic velocity is a function of elastic moduli and density)	Acoustic velocity-depth model often with interpreted layer boundaries	Geologic profile
Cross-hole seismic tomography	Travel times and amplitudes of seismic energy (p- or s- wave)	Density and acoustic velocity (acoustic velocity is a function of elastic moduli and density)	Model depicting spatial variations in acoustic value	Geologic profile
Multichannel analyses of surface waves (MASW)	Travel times of surface wave energy generated using an active source (e.g., sledge hammer)	Acoustic velocity (function of elastic moduli and density)	Acoustic (shear-wave) velocity-depth model often interpreted layer boundaries	Geologic profile
Refraction micro-tremor (ReMi)	Travel times of passive surface wave energy	Acoustic velocity (function of elastic moduli and density)	Acoustic (shear-wave) velocity-depth model often with interpreted layer boundaries	Geologic profile

Table 2.9: Summary of 12 commonly used geophysical surveying methods for geotechnical investigations (Anderson et al., 2008) (continued)

Geophysical Method	Measured Parameter(s)	Physical Property or Properties	Physical Property Model (Geotechnical Application)	Typical Site Model (Geotechnical Application)
Ground penetrating radar (GPR)	Travel times and amplitudes of reflected pulsed EM energy	Dielectric constant, magnetic permeability, conductivity and EM velocity	EM velocity/depth model with interpreted layer boundaries	Geologic profile
Electro-Magnetics (EM)	Response to natural- induced EM energy	Electrical conductivity and inductivity	Conductivity-depth model often with interpreted layer boundaries	Geologic-hydrologic profile
Electrical resistivity	Potential differences in response to induced current	Electrical resistivity	Resistivity-depth model often with interpreted layer boundaries	Geologic-hydrologic profile
Induced polarization (IP)	Polarization voltages or frequency dependent ground resistance	Electric capacitivity	Capacitivity-depth model	Model depicting spatial variations in clay content (or metallic mineralization)
Self potential (SP)	Natural electrical potential differences	Natural electric potentials	Model depicting spatial variation in natural electric potential of the subsurface	Hydrologic model (seepage through dam, levee, or fractured bedrock, etc.)
Magnetics	Spatial variations in the strength of the geomagnetic field	Magnetic susceptibility and remanent magnetization	Model depicting spatial variations in magnetic susceptibility of subsurface	Geologic profile or map (location of faults, variable depth to bedrock, etc.)
Gravity	Spatial variations in the strength of gravitational field of the Earth	Bulk density	Model depicting spatial variations in the density of the subsurface often with interpreted layer boundaries	Geologic profile or map (location of voids, variable depth to bedrock, etc.)

2.6 Seismic

Seismic is the propagation of elastic waves through the earth or other planet-like bodies. Seismic is normally used to study earthquake effects, volcanic, tectonic, oceanic, atmospheric, and artificial process such as explosions. Seismic test methods are relatively new for stabilizing soil, and most of the tests carried out have been exploratory nature. The tests employ seismic wave, P-wave, S-wave, Love wave and Rayleigh waves.

2.6.1 Seismic waves

Seismic waves are waves of energy that travel through the Earth's layers, and are a result of an earthquake, explosion, or a volcano that imparts low-frequency acoustic energy. There are many types of seismic waves, such as, compressional body waves (P-waves), shear body waves (S-waves), Love waves (L-waves), Rayleigh waves (R-waves), etc. The P-waves and S-waves are categorized as body waves while R-waves and L-waves are surface waves. Seismic waves propagate at a rate governed by material properties such as bulk and shear moduli and density. Figure 2.1 shows example of particle motion waves pass through a medium.

The seismic waves is generated by a seismic sources which radiate pulses of energy spherically (in all directions) from a source point. The situation is best described by a pebble drop into water. The energy movement causes the occurrence of wave front. The wave front is the boundary between the energy pulse and the material that has not yet received the energy. Part of wave front is a seismic ray which is the path of a tiny portion of the wave front that is perpendicular to wave front. Figure 2.2 shows the seismic wave front and seismic ray.

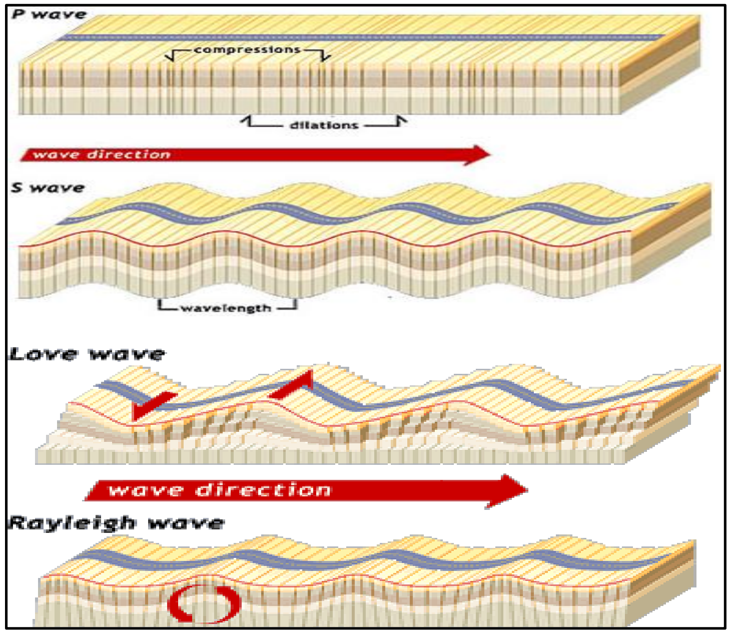

Figure 2.1: The particle motions when the seismic waves pass the medium (Central Weather Bureau, 2012)

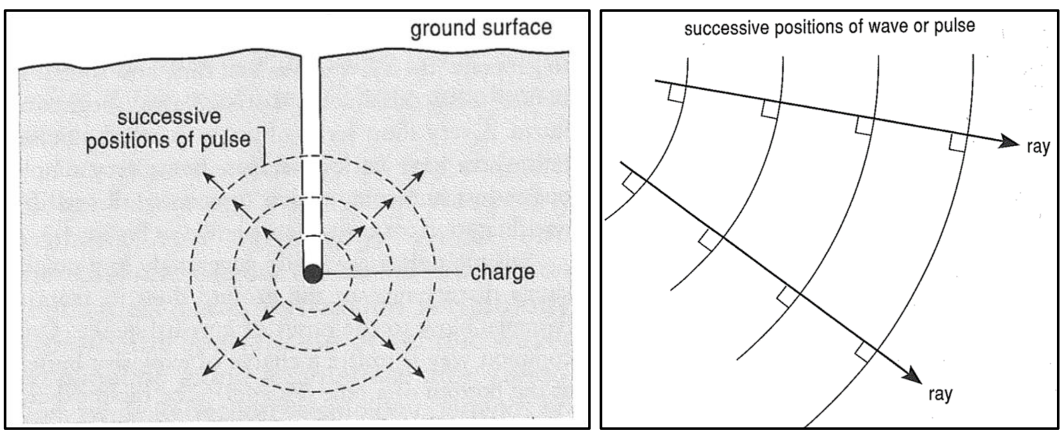

Figure 2.2: Seismic wave front and seismic ray

2.6.1.1 Rayleigh wave

Rayleigh waves were founded by Lord Rayleigh in 1885. Lord Rayleigh described the propagation of a surface wave along the free surface of a semi-infinite elastic half-space (Lowrie, 2007). Rayleigh-wave phase velocity of a layered earth model is a function of frequency and four groups of earth properties namely P-wave velocity (V_p), S-wave velocity (V_s), density (ρ), and thickness (h) of layers. Rayleigh waves is a surface shear waves that makes the ground move up and down in a retrograde elliptical pattern as shown in Figure 2.1. According to Xia et al. (1999), Rayleigh waves are the result of interfering P and S_v waves. Particle motion is constrained to the vertical plane consistent with the direction of wave propagation. In addition, Rayleigh wave has smaller attenuation, high S/N ratio, stronger immunity of interference and shear wave velocity is the dominant property (Luo et al., 2009). The longer wavelength surface waves penetrate deeper into the earth compared to the shorter wavelength (Pei et al., 2006). The strong particle motion close to the surface of Rayleigh wave is attenuated with depth (Bessason and Erlingsson, 2011). The inversion of the dispersive phase velocity of the surface (Rayleigh and/or Love) wave will produce the S-wave velocity (Xia et al., 1999).

2.6.2 Seismograph

The seismograph is an equipment used by seismologists to measure the ground acceleration of the Earth. The records of the arrival times of seismic waves recorded by the seismograph is called seismogram. Figure 2.3 shows a various seismic waves arrival times created by a seismograph which is shown by the seismogram image.

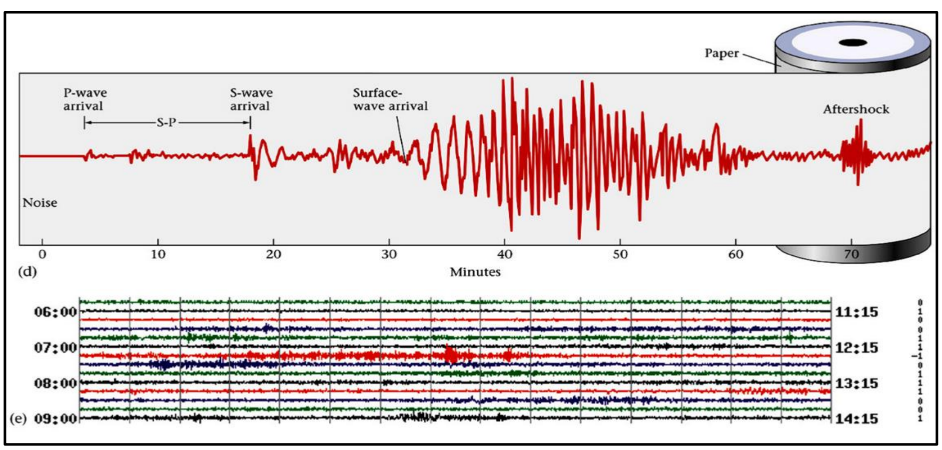

Figure 2.3: Seismic waves recorded by seismogram

2.7 Multichannel analysis of surface waves (MASW)

MASW is a seismic exploration method evaluating ground stiffness in 1-D, 2-D, and 3-D formats for various types of Geotechnical engineering projects. Since its first introduction in the late 1990s by the Kansas Geological Survey (Park et al., 1999), it has been utilized by many practitioners and researched by many investigators worldwide. The MASW exploits multichannel recording and processing techniques in order to solve the problem associated with the Spectral Analysis of Surface Waves (SASW) (Huang and Mayne, 2008). According to Xia et al., (2002), MASW is an environmentally-friendly method for estimation of shear-wave velocity with depth. It is also economically reliable compared to several other method. This survey deals with surface waves in the lower frequencies range 1-30 Hz and much shallower depth of investigation (Park et al., 2007). In the matter of time for example, MASW method needed approximately a few minutes to obtain the data.

2.7.1 Active MASW method

The active MASW method generates surface waves actively through an impact source like a sledge hammer. This method is time efficient as the result can be obtained directly. Figure 2.4 shows an illustration of different type of waves in MASW method. The investigation depth is usually less than 30 m (Park et al., 2007). The data acquisition for active MASW survey is related to several parameters. The list of the optimum parameters for the data acquisition is as shown in Table 2.10. Although slight variation in any parameter could happen at different site or condition.

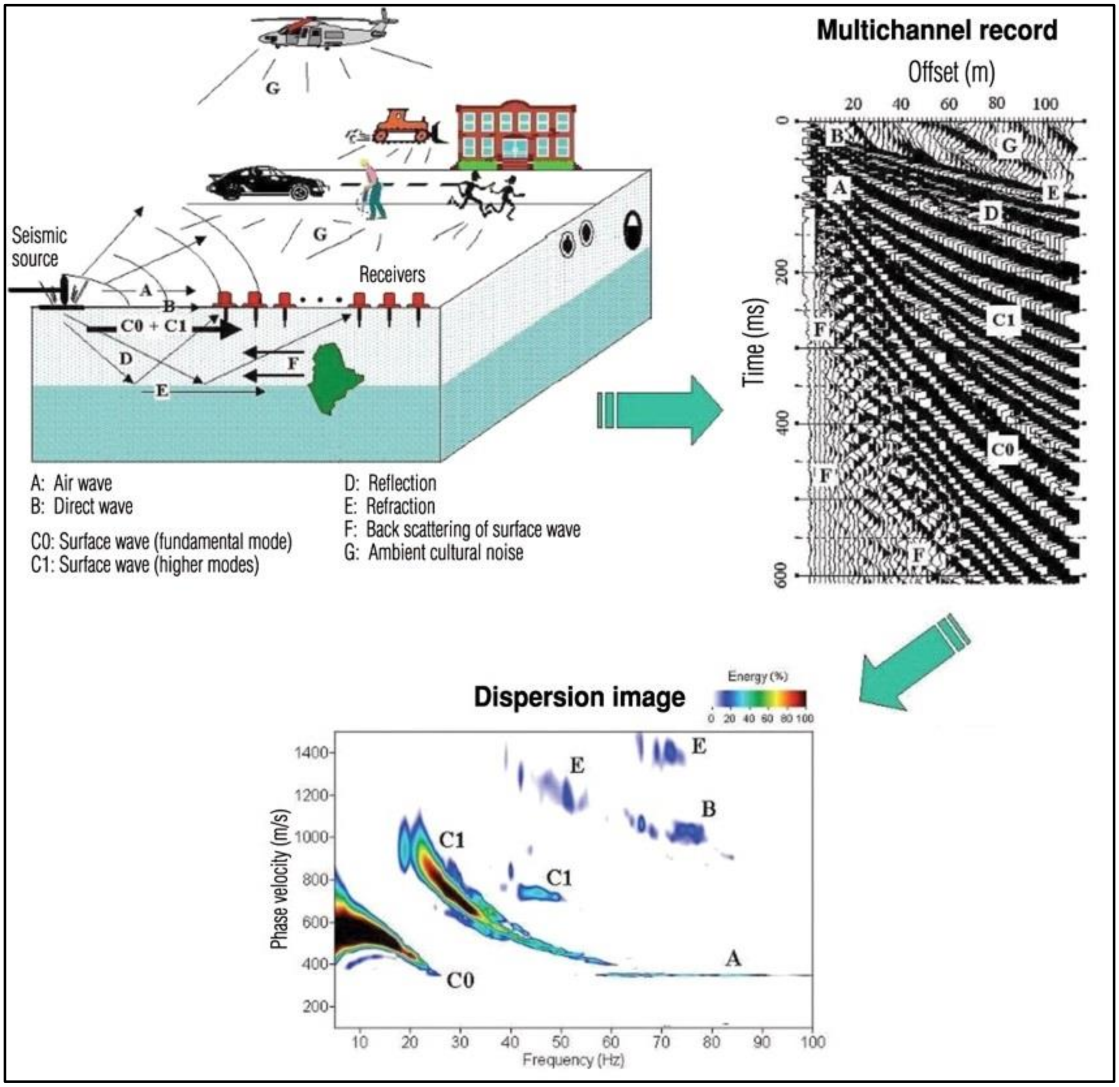

Figure 2.4: An illustration of different types of waves in MASW method (Penumadu and Park, 2005)

Table 2.10: Data acquisition parameters for active MASW survey (in meters) (Park Seismic LLC., n.d.)

Depth (Z_{max})[1] (m)	**Source (S)[2] (lb)**	**Receiver (R)[3] (Hz)**	**Receiver Spread (RS) (m)**				**SR Move[6] (dx)**			**Recording[8]**				
			Length[4] (D)	**Source offset[5] (X_1)**	**Receiver Spacing (dx)**		**Lateral Resolution[7]**			**dt[9] (ms)**	**T[10] (sec)**	**Vertical Stack[11]**		
					24-ch*	**48-ch**	**High**	**Medium**	**Low**			**C**	**N**	**VN**
≤ 1.0	≤ 1	4.5-100	1-3	0.2-3.0	0.05-0.1	0.02-0.05	1-2	2-4	4-12	0.5-1.0	0.5-1.0	1-3	3-5	5-10
	(1)**	**(40)**	**(2.0)**	**(0.4)**	**(0.1)**	**(0.05)**	**(1)**	**(2)**	**(4)**	**(0.5)**	**(0.5)**	**(3)**	**(5)**	**(10)**
1-5	1-5	4.5-40	1-15	0.2-15	0.05-0.6	0.02-0.3	1-2	2-4	4-12	0.5-1.0	0.5-1.0	1-3	3-5	5-10
	(5)	**(10)**	**(10)**	**(2)**	**(0.5)**	**(0.25)**	**(1)**	**(2)**	**(4)**	**(0.5)**	**(0.5)**	**(3)**	**(5)**	**(10)**
5-10	5-10	≤ 10	5-30	1-30	0.2-1.2	0.1-0.6	1-2	2-4	4-12	0.5-1.0	0.5-1.0	1-3	3-5	5-10
	(10)	**(4.5)**	**(20)**	**(4)**	**(1.0)**	**(0.5)**	**(1)**	**(2)**	**(4)**	**(0.5)**	**(0.5)**	**(3)**	**(5)**	**(10)**
10-20	≥ 10	≤ 10	10-60	2-60	0.4-2.5	0.2-1.2	1-2	2-4	4-12	0.5-1.0	1.0-2.0	1-3	3-5	5-10
	(20)	**(4.5)**	**(30)**	**(10)**	**(1.5)**	**(1.0)**	**(1)**	**(2)**	**(4)**	**(0.5)**	**(0.5)**	**(3)**	**(5)**	**(10)**
20-30	≥ 10	≤ 4.5	20-90	4-90	0.8-3.8	0.4-1.9	1-2	2-4	4-12	0.5-1.0	1.0-2.0	1-3	3-5	5-10
	(20)	**(4.5)**	**(50)**	**(10)**	**(2.0)**	**(1.5)**	**(1)**	**(2)**	**(4)**	**(1.0)**	**(1.0)**	**(3)**	**(5)**	**(10)**
30-50	≥10**(20)**	≤ 4.5	30-150	6-150	1.2-6.0	0.6-3.0	1-2	2-4	4-12	0.5-1.0	1.0-3.0	1-3	3-5	5-10
	or passive	**(4.5)**	**(70)**	**(15)**	**(3.0)**	**(2.0)**	**(1)**	**(2)**	**(4)**	**(1.0)**	**(1.0)**	**(3)**	**(5)**	**(10)**
> 50	≥10**(20)**	≤ 4.5	> 50	> 10	> 2.0	> 1.0	1-2	2-4	4-12	0.5-1.0	≥ 1.0	1-3	3-5	5-10
	or passive	**(4.5)**	**(150)**	**(30)**	**(6.0)**	**(4.0)**	**(1)**	**(2)**	**(4)**	**(1.0)**	**(2.0)**	**(3)**	**(5)**	**(10)**

*Recommended values in "( )

2.8 Factors influencing MASW data acquisition

In every research, there are always factors that affect the testing or result obtained. Careful action need to be taken to minimize the error caused by these factors. In this subtopic, several factors that related to MASW data acquisition are stated and discussed. Those factors are seismograph setting, equipment configuration, topography, and dispersion curve plotting.

2.8.1 Seismograph configuration

The seismograph is an equipment used to record the waves received by the sensor. In this study, ABEM Terraloc MK8 is used to record the waves. The critical configuration for the seismograph involved the acquisition setup, receiver spread and layout geometry.

2.8.1.1 Acquisition setup

The acquisition setup interface involves the configuration for the setup, trig, noise and filters. For the setup, it involves the sampling interval, number of samples, pre-trig or delay, number of stacks, stack mode and re-arm mode. The pre-trig or delay, stack mode and re-arm mode, can be configured according to the needs during the data acquisition. The sampling interval and number of sample are critical as it will determine the recording time for each data set. Short recording time will cause incomplete data set recorded. While, long recording time increase the possibility of recording ambient noise (Taipodia and Dey, 2012). Table 2.11 shows some sample interval and record length used by earlier researchers.

Table 2.11: Sample interval and record length used by previous researchers

Author (Year)	Type of soil	Total receiver length (m)	Nearest offset (m)	Sample interval (μs)	No of samples
(Madun et al., 2016)	Marine clay	23 and 115	2 and 5	250 – 500	4096 - 8192
(Xia et al., 2003)	-	28.8 and 30	5 and 9	1024	1024 - 2048

The number of stacks is determined according to the environment and type of soil involves. When the environment involves high noise due to traffic such as at urban location, high number of stacking is needed to increase the signal-to-noise ratio. Limited noise such as at rural area need less number of stacking as the signal-to-noise ratio is already high. However, the type of soil also affect the determination of number of stacking. Weak soil such as highly organic soil will interrupt the wave travel during data acquisition which directly affect the S/N ratio. Therefore, by increasing the number of stacking will improved the S/N ratio. As for the hard soil, the wave travel will be less affected which provide high signal-to-noise ratio.

The trigger setup involved the configuration of trig input mode, trig input level, external trig/arm out mode and verify timeout (ms). High value of input level increased the sensitivity of the trigger which means lower signal level is needed to trig the terraloc ("Seismic System Reference Manual for ABEM Terraloc ® Mk6 v2 and Mk8 with ABEM SeisTW for Windows XP ® 2009-05-19," 2009). The environment noise should also be consider to prevent auto-trigger due to high sensitivity trigger. The noise monitor can be set on or off. However, it is recommended to turn it on to allow noise monitoring before and during data acquisition. The damping value define the sensitivity of the recorder. Lower damping value will increase the sensitivity of source detection. But, with the presence of high noise, it is recommended to set higher value to prevent auto-triggered by the noise. The threshold level does not affect much in this study, therefore, it is set as zero.

The filter setting allows the data filtering during data acquisition. However, it is best to turn of this setting to produce high quality data with minimum altering. This is to provide engineer with the real in-situ data.

2.8.1.2 Receiver spread

The receiver spread interface is used to ensure the trace number and the channels are synchronize accordingly to allow correct wave data set recorded. Wrong synchronization will cause the recorded waves to be placed at different location. Although this action is reversible during the data analysis, proper configuration will ease the process and save time.

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